Detecting Pop. III Stars with HARMONI on the ELT

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Julien Devriendt
Miguel Pereira-Santaella
Population III Stars

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**Population III Stars**

![Graph showing the mass function of PopIII stars compared to PopI and PopII stars.](image)
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★ Needed for galaxy evolution (i.e. to produce metals for future star formation) theories
★ Due to large mass, Pop. III stars have the potential to completely ionise He.
Signature of Pop. III Stars: He\(\text{II}\)\(\lambda\)1640

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**SEDs from Zackrisson et al., 2016**
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Signature of Pop. III Stars: HeII$\lambda$1640

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★ HeII$\lambda$1640 recombination line possible as signature.
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SEDs from Zackrisson et al., 2016
First light general purpose Integral Field Spectrograph for ELT

V-K (0.45 – 2.45\(\mu\)m) spectral coverage

R=3500, 7000, 17000 resolutions

60, 20, 10 & 4 mas pixel scales

NoAO/LTAO/SCAO correction

206x152 pixel field of view (image slicer with 32000 spaxels)
First light general purpose

### Instrument

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<th>Parameter</th>
<th>Value</th>
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### Telescope

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<td>Telescope Temperature [K]</td>
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### Miscellaneous

- Subtract Background: false
- Return Object Cube: false
- Return Transmission Cube: false
- No. of processors (1-32): 31
- Noise Seed: 0
- Set Spec Samp [A/pix]: 0
- Additional PSF Blur [mas]: 0

(image slicer with 32000 spaxels)

All of which is simulated with HSIM (see Zieleniewski et al., 2015)
First light general purpose Instrument

HARMONI wavelength range: \(0.45 \leq \lambda \leq 2.45\mu m\)

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First light general purpose

HARMONI wavelength range: $0.45 \leq \lambda \leq 2.45\mu m$

HeII$\lambda 1640$ for $3 \leq z \leq 10 \rightarrow 0.656 \leq \lambda \leq 1.8\mu m$

(image slicer with 32000 spaxels)

All of which is simulated with HSIM (see Zieleniewski et al., 2015)
NewHorizon Simulation

- New cosmological Hydrodynamical + N-Body simulation
- Run from $z \sim 45$ to $z \sim 0.7$ with a volume of $20\text{MPc}$
- Use the Adaptive Mesh Refinement code RAMSES (Teyssier, 2002).
- Includes: Gas, Dark Matter, Stars particles, Black Holes, star formation, stellar feedback and AGN feedback.
- It has a maximum spatial resolution of $\Delta x \sim 35\text{pc}$ and a mass resolution of $2 \times 10^5 M_\odot$
- See Dubois et al., in prep and references within

Image credit: Y. Dubois for the NewHorizon collaboration

10 Comoving Mpc
1) Run grid of CLOUDY simulations using the predicted SEDs
Modelling Observations of Pop. III stars

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2) Select galaxies from the NewHorizon Simulation

* stars in the simulation are in fact star particles with mass of $10^4 \lesssim M_\star \lesssim 10^5 M_\odot$
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★ >50% Pop. III stars

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★ Mean Pop. III age < $2 \times 10^6$ Myr

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3) Identify each star* as either PopIII or PopII

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4) Combine CLOUDY runs with NewHorizon to produce observable objects.

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2) Select galaxies from the NewHorizon Simulation
3) Identify each star* as either PopIII or PopII
4) Combine CLOUDY runs with NewHorizon to produce observable objects.
5) Observe the simulation using HSIM

* stars in the simulation are in fact star particles with mass of $10^4 \lesssim M_\star \lesssim 10^5 M_\odot$
Observing Pop. III Stars
Recovered Galaxy Spectrum

White Dashed Contour: \( \Sigma_{\star} \geq 1 \, M_\odot \)

White Solid Contour: \( \Sigma_{\star} \geq 100 \, M_\odot \)

Grisdale et al., in prep
Recovered Galaxy Spectrum

White Dashed Contour: $\Sigma_* \geq 1 M_\odot$

White Solid Contour: $\Sigma_* \geq 100 M_\odot$

Cyan Dashed Contour: $\Sigma_{\text{gas}} \geq 10^{1.5} M_\odot$

Cyan Solid Contour: $\Sigma_{\text{gas}} \geq 10^{2.5} M_\odot$

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Recovered Galaxy Spectrum

He$\lambda$1640
FWHM = 29.331 km s$^{-1}$
$F_{\text{peak}}/F_{\text{cont.}} = 54.194$

White Dashed Contour: $\Sigma_\star \geq 1 \, M_\odot$
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Grisdale et al., in prep
Can HeII 1640 be observed?

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10 Hour observation with HSIM

Grisdale et al., in prep
Can HeII1640 be observed?

He\(\lambda\)1640
FWHM = 29.331 km s\(^{-1}\)
\(F_{\text{peak}}/F_{\text{cont.}} = 54.194\)

Grisdale et al., in prep
Can HeII1640 be observed?

FWHM = 111.503 km s\(^{-1}\)

\(N_{\text{peak}}/N_{\text{cont.}} = 13.344\)

Spaxel Scale : 10 \(\times\) 10

Grisdale et al., in prep
Observations at Multiple Redshifts

G1, z = 10
FWHM = 119.328 km s\(^{-1}\)
\(N_{\text{peak}}/N_{\text{cont.}} = 5.591\)
Spaxel Scale : 10 \(\times\) 10

G2, z = 9
FWHM = 128.332 km s\(^{-1}\)
\(N_{\text{peak}}/N_{\text{cont.}} = 118.065\)
Spaxel Scale : 10 \(\times\) 10

G3, z = 8
FWHM = 198.194 km s\(^{-1}\)
\(N_{\text{peak}}/N_{\text{cont.}} = 5.553\)
Spaxel Scale : 10 \(\times\) 10

G4, z = 7
FWMH = 118.065 km s\(^{-1}\)
\(N_{\text{peak}}/N_{\text{cont.}} = 5.591\)
Spaxel Scale : 10 \(\times\) 10
Observations at Multiple Redshifts

- **G5, \( z_6 \)**
  - FWHM = 126.055 km s\(^{-1} \)
  - \( N_{\text{peak}}/N_{\text{cont.}} = 14.701 \)
  - Spaxel Scale: 10 × 10

- **G6, \( z = 5 \)**
  - FWHM = 176.890 km s\(^{-1} \)
  - \( N_{\text{peak}}/N_{\text{cont.}} = 1.337 \)
  - Spaxel Scale: 20 × 20

- **G7, \( z = 4 \)**
  - Spaxel Scale: 20 × 20

- **G8, \( z = 3 \)**
  - FWHM = 103.918 km s\(^{-1} \)
  - \( N_{\text{peak}}/N_{\text{cont.}} = 4.236 \)
  - Spaxel Scale: 20 × 20
Impact of IMF
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\[ \Phi(M) \]

\[ \Phi M[M_\odot] \]

- PopIII.1
- PopIII.2
- PopIII.K & PopII.K
★ 6 of 8 galaxies still produce HeII\(\lambda 1640\) but in all cases the line strength is weaker.
Impact of IMF: PopIII.2

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★ Only 4 of the 8 are now observable.
Impact of IMF: PopIII.2

G1, $z = 10$
FWHM = 137.136 km s$^{-1}$
$N_{\text{peak}}/N_{\text{cont.}} = 3.401$
Spaxel Scale: $10 \times 10$

G2, $z = 9$
FWHM = 116.580 km s$^{-1}$
$N_{\text{peak}}/N_{\text{cont.}} = 5.538$
Spaxel Scale: $10 \times 10$

G3, $z = 8$
FWHM = 183.340 km s$^{-1}$
$N_{\text{peak}}/N_{\text{cont.}} = 2.482$
Spaxel Scale: $10 \times 10$

G5, $z = 6$
FWHM = 112.869 km s$^{-1}$
$N_{\text{peak}}/N_{\text{cont.}} = 29.941$
Spaxel Scale: $10 \times 10$
Some galaxies produce extremely weak emission lines.
★ Some galaxies produce extremely weak emission lines.
★ However none are observable.

Impact of IMF: PopIII.K

\[
\phi(M) = \begin{cases} 
10^3 & \text{for PopIII.1} \\
10^2 & \text{for PopIII.2} \\
10^0 & \text{for PopIII.K & PopII.K} 
\end{cases}
\]
Detection Requirements

\[ F_{\text{peak}} \geq 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \]
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- $F_{\text{peak}} / F_{\text{cont.}} > 1.4$
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★ $20 \leq \text{FWHM} \leq 100 \text{km s}^{-1}$
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- \( 20 \leq \text{FWHM} \lesssim 100 \text{ km s}^{-1} \)

In all cases, HeII\( \lambda 1640 \) detection will require target candidates from preceding observations.
**Summary**

Take aways:

★ Using High-res cosmological simulations, and HSIM it is possible to model observations of the PopIII for a given IMF and set of SEDs.

★ If the IMF of Pop. III stars is top heavy they will be detectable in observations via the HeII$\lambda 1640$ emission line for $3 \leq z \leq 10$.

★ If Pop. III stars follow a “traditional” IMF they are unlikely to be observed via the HeII$\lambda 1640$ emission line at any $z$.

★ Morphology of such galaxies is unlikely to be resolved.

★ Emissions form galaxies need to have $F_{\text{peak}} \geq 10^{-16} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$, $F_{\text{peak}}/F_{\text{cont.}} > 1.4$ and $20 \leq \text{FWHM} \leq 100 \text{km s}^{-1}$ to be detectable.

Still to come:

★ “Observing” HeII$\lambda 1640$ in multiple galaxies at a given redshifts. Does Size/morphology etc. matter?

★ What impact does AGN have on the Pop. III signal.

★ Will observations provide constraints on PopIII IMFs?
Near-IR Spectroscopy with the ELTs
21-24 Sep 2020
Dept of Physic sOxfor d
Save the date!

Science cases & simulations

High-z SNe: Boussinou et al 2018

CGM: Augustin et al, MNRAS acc

Resolved Stellar pops: Gonzalez

High-z Kinematics: Kendrew et al. 2016
Richardson et al. subm

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